TD 93-1366

TNO Defence Research

P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Fax +31 3463 5 39 77
Telephone +31 3463 5 62 11

TNO-report

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A.H. Wertheim
R. Heus
T.G.M. Vrijkotte
J.T. Marcus

THE EFFECT OF PLATFORM MOTION ON HUMAN ENERGY EXPENDITURE DURING WALKING. AN EXPLORATORY EXPERIMENT

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CONTENTS

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Title:	The effect of platform motion on human energy expenditure during walking. An exploratory experiment
Authors:	Dr. A.H. Wertheim, Drs. R. Heus, Drs. T.G.M. Vrijkotte and Dr. J.T. Marcus
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SUMMARY

An experiment was performed in which various physiological measures of energy expenditure were taken with subjects walking for periods of 10 minutes (either freely or on a treadmill) on a moving platform (Ship Motion Simulator). Platform motion was either in a heave, pitch or roll mode, or it was stationary. The results show that during pitch and roll movements of the platform energy expenditure is larger than during heave motions and when the platform remained stationary. Pitch and roll did not differ from each other, and neither did heave and stationary conditions. The results are interpreted as indicating that the muscular effort needed for the maintenance of balance when walking on a pitching or rolling platform requires a significant increase in energy expenditure.

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Instituut voor Zintuigfysiologie TNO
Soesterberg

Het effect van platformbewegingen op het menselijk energieverbruik tijdens lopen. Een eerste experimentele studie

A.H. Wertheim, R. Heus, T.G.M. Vrijkotte en J.T. Marcus

SAMENVATTING

Een experiment werd uitgevoerd waarbij met behulp van diverse fysiologische maten het energieverbruik werd gemeten van proefpersonen die gedurende 10 minuten liepen (vrij of op een tredmolen) op een bewegend platform (Scheeps-bewegingssimulator). De bewegingen van het platform waren in de heave, pitch of roll mode en in één conditie bleef het platform bewegingloos. De resultaten lieten zien dat tijdens pitch en roll bewegingen het energieverbruik groter is dan tijdens heave condities en wanneer het platform stil staat. Er waren geen verschillen tussen pitch en roll condities en de heave conditie verschilde niet van stilstand. De resultaten worden geïnterpreteerd als indicatief voor een significante toename in spierarbeid die moet worden verricht bij het handhaven van het houdingsevenwicht tijdens lopen op een in roll of pitch richting bewegend oppervlak.

1 INTRODUCTION

The question to what extent ship operational performance at sea is affected by possible decrements in performance of its crew due to the movements of the ship, has only in the recent years become an issue of research. Some attempts have been made to investigate performance decrements which might indicate increased workload in relation to sea-sickness (Bles et al., 1988, 1991), and a measure has been developed to operationalize performance decrements in terms of so called Motion Induced Interruptions, or MII's (e.g. Graham, 1990). However, to our knowledge no attempts have been made to investigate the possibility that physiological energy consumption is affected by the extra effort required for normal performance during ship motion. The present study was designed as a first step in this direction.

The TNO Institute for Human Factors IZF has a long research tradition of measuring physiological energy consumption during human performance. Recently, the institute also acquired a ship motion simulator (SMS) that consists of a large experimental cabin which can move in pitch, roll and heave. Thus it became possible to investigate whether—and to what extent—particular movements of the SMS might affect physiological energy consumption during a simple task, such as walking.

The physiological indices of energy consumption chosen for this study were various ventilatory parameters (oxygen consumption, carbon dioxide production, minute ventilation and metabolism) and heart rate. These are all well known indices of energy consumption (Åstrand, 1986). Subjects were required to simply walk to and fro alongside the length of the cabin floor, or to walk on a treadmill. The question investigated was whether heave, roll and pitch movements of the SMS would enhance the energy consumption of the subjects as compared to a condition in which the SMS remained motionless. Since this was only a first exploratory experiment it was decided not to make the SMS movements too complicated. Hence we used only three SMS motion conditions (heave, roll, pitch) and one control condition in which the SMS remained stationary. Combinations of pitch, roll and/or heave were not included.

2 METHOD

2.1 The Ship Motion Simulator (SMS)

The SMS consists of a large cabin (length 4.0 m, width 2.4 m and height 2.6 m), placed on a hydraulic system which enables pitch, roll and heave movements of the whole cabin (separately or in any combination). The distance from cabin floor to the rotation axes of pitch and roll is 1.8 m (which means that roll and pitch movements give rise to translational movements as well). The maximum

amplitudes of motion are approximately 0.5m in heave, 20° in pitch, and 15° in roll. The frequency range of pitch, roll and heave motions is restricted and depends on the particular combination of motions programmed. Since the cabin is not placed symmetrically on the central carrying piston of the hydraulic system, its frontal side is able to cover a larger vertical distance during pitch motion than its rear side.

All SMS motions were sinusoidal (see Table I), and their profiles were generated and controlled by computer, with closed-loop feedback of cabin displacement.

Table I Motion stimulus conditions applied in the experiment. Motion was always sinusoidal with a frequency of 0.125 Hz. Note the parasitical heave component in the pitch and roll conditions, and the parasitical translation force in the roll condition. g = 9.81 m/s².

Condition	Amplitude	Parasit. heave	Parasit. translation
Heave	± 0.31m (± 0.02g)	0	0
Pitch	± 5°	± 0.015g	0
Roll	± 5°	± 0.003g	± 0.02g
Stationary	0	0	0

The *parasitical heave* components in the pitch and roll conditions are induced by the vertical acceleration component of the cabin motion. The values for parasitical heave in the above table are the peak values to which subjects are exposed when they are maximally displaced from the centre of rotation. As mentioned above, in the pitch condition this may occur when the subject is walking on the floor of the cabin, i.e. when he or she happens to arrive at the frontal side of the cabin at the moment of peak vertical parasitical heave of this side.

The *parasitical translation* component in roll is induced by the lateral acceleration component of cabin motion. This component is relatively large, because of the large distance between the roll axis and the cabin floor (see above). Its peak value as given in the table applies to the subject's head (assumed to be at 1.8 m above the cabin floor), assuming that he or she stays vertical relative to the cabin floor. During postural corrections—i.e. when the subject attempts to align his or her body axis with the true vertical (the earth's gravity)—the translational force may become less (the minimal parasitical translation is then 0.01g). In the roll condition the subject is exposed continuously to this parasitical force.

2.2 Walking conditions

The subjects were instructed to walk in the cabin in two different conditions: On a treadmill, and on the cabin floor along the length axis of the cabin. The treadmill was located such that the subject walking on it was positioned approximately 0.5m aside the centre of rotation of the cabin. On the treadmill, walking speed was set at 1m/s. In conditions where subjects had to walk on the floor, they had to turn around each time they reached the frontal or backside wall of the cabin. The approximate turning point was marked on the floor at 0.5 meter distance from the cabin walls. The single path length on the floor was thus 3m. In order to keep a stable walking speed, approximately equal to that on the treadmill, a brief sound beep was generated every 6s. Subjects were required to synchronize their walking to this beep, covering the length of the cabin twice (once in each direction) in exactly one beep interval.

2.3 Physiological measurements

The ventilatory parameters of oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and minute ventilation ($\dot{V}_E$) were measured with an Oxycon Σ (Mijnhardt BV) in the mixing chamber mode. The subjects were connected to the Oxycon with a flexible tube (for support, the tube was belted to the subjects waist) attached airtight to a full face mask with low breathing resistance. The Oxycon apparatus itself was placed inside the SMS cabin and was connected with its control panel and computer in the control room of the SMS.

Because flexible tube was quite long, measurements of the ventilatory parameters only started after an initial period of approximately 5 minutes, during which the level of the parameters was monitored, until it reached a steady state. The actual experimental measurement period lasted approximately 10 minutes.

The ventilatory parameters were obtained separately, and also served to calculate RQ values commonly used in the following index of metabolism (ISO 8996):

$$\text{Metabolism (Watts)} = \frac{(0.23 * RQ + 0.77) * 21.14 * \dot{V}_{O_2}}{60}$$

where RQ = respiratory quotient ($= \dot{V}CO_2/\dot{V}O_2$)

Heart rate was registered with a wireless Sporttester PE4000 (Polar Electro OY) using an electrode belt around the chest of the subjects.

2.4 Procedure

The experiment was designed to determine possible effects of (and interactions between) SMS motion (heave, pitch, roll and stationary) and the way of walking in the simulator (treadmill or cabin floor), on the physiological energy consumption indices. The sequence of conditions for the twelve subjects was balanced for motion and walking conditions (latin square, to prevent confounding of experimental effects with possible effects of fatigue), as shown in Table II.

A complete SMS motion condition (including both f and t subconditions) lasted for a period of approximately 25 minutes. The condition started with a 5 minute adaptation period. After this period the condition continued for 10 minutes during which the actual measurements were taken and recorded. The experimenter then instructed the subject—using an intercom system—to change position (i.e. to step on or off the treadmill). That subcondition then lasted for another 10 minutes of measurement and recording.

Table II Sequence of conditions.

Subject	1st cond	2nd cond	3rd cond	4th cond
1	S(f,t)	H(t,f)	R(f,t)	P(t,f)
2	S(t,f)	H(f,t)	R(t,f)	P(f,t)
3	S(f,t)	H(t,f)	R(f,t)	P(t,f)
4	H(t,f)	P(f,t)	S(t,f)	R(f,t)
5	H(f,t)	P(t,f)	S(f,t)	R(t,f)
6	H(t,f)	P(f,t)	S(t,f)	R(f,t)
7	R(f,t)	S(t,f)	P(f,t)	H(t,f)
8	R(t,f)	S(f,t)	P(t,f)	H(f,t)
9	P(f,t)	R(t,f)	H(f,t)	S(t,f)
10	P(t,f)	R(f,t)	H(t,f)	S(f,t)
11	R(f,t)	S(t,f)	P(f,t)	H(t,f)
12	P(t,f)	R(f,t)	H(t,f)	S(f,t)

S stationary cabin
H heave
R roll
P pitch
f walking on cabin floor
t walking on treadmill

The sequential order of the f and t conditions between brackets reflects the temporal consecutive order in which the f and t conditions were given. Gender was randomly assigned.

2.5 Subjects

Eight healthy male and four healthy female subjects participated in this study. The subjects had a mean age of 24 years (range 19 - 40 years), mean length was 179cm (range 160 - 195cm) and mean weight 71.6kg (range 57 - 95kg). Mean fat percentage of the subjects, as measured with the skinfold method (Durnin & Wormersley, 1974) was 16% (range 5.0 - 25%). All subjects wore rubber soled sneakers.

During the experiment the inside of the cabin was continuously monitored (and recorded) with two video cameras positioned in the middle upper positions of the front and the rear walls of the cabin. Together the images of these cameras covered the complete inside volume of the cabin, including the subject, the Oxycon apparatus and the treadmill. The video images were displayed together with an outside image of the cabin (made by a separate video camera), and a display of the control computer on which the SMS monitoring signals were made visible. An example of the resulting composite video-image during SMS roll motion is shown in Fig. 1.

The inside walls of the SMS cabin and the Oxycon apparatus were padded with foam rubber for protection against injury in case a subject might lose balance. The treadmill was equipped with handrails for support on both sides. All subjects were extensively informed about the purpose and procedures of the study and gave their written consent to participate. They were informed that they were at any time allowed to discontinue the experiment in case they felt uneasy or nauseous. The SMS cabin was continuously ventilated with fresh air from the outside.

3 RESULTS

Only one subject reported feelings of nausea during experimentation, although not severe enough to discontinue the experiment. Since the physiological parameters of this subject were not discernably different from those of the other subjects, his data were not treated separately.

The data were submitted to an analysis of variance (using CSS software and after checking the homogeneity of variance), using SMS motion (4 levels), walking mode (2 levels), and gender (2 levels) as input variables. If an SMS motion variable (or its interaction with any other variable) had a significant effect ($p<.05$), the differences among its levels were tested separately for significance with a Tukey post-hoc test ($p<.05$).

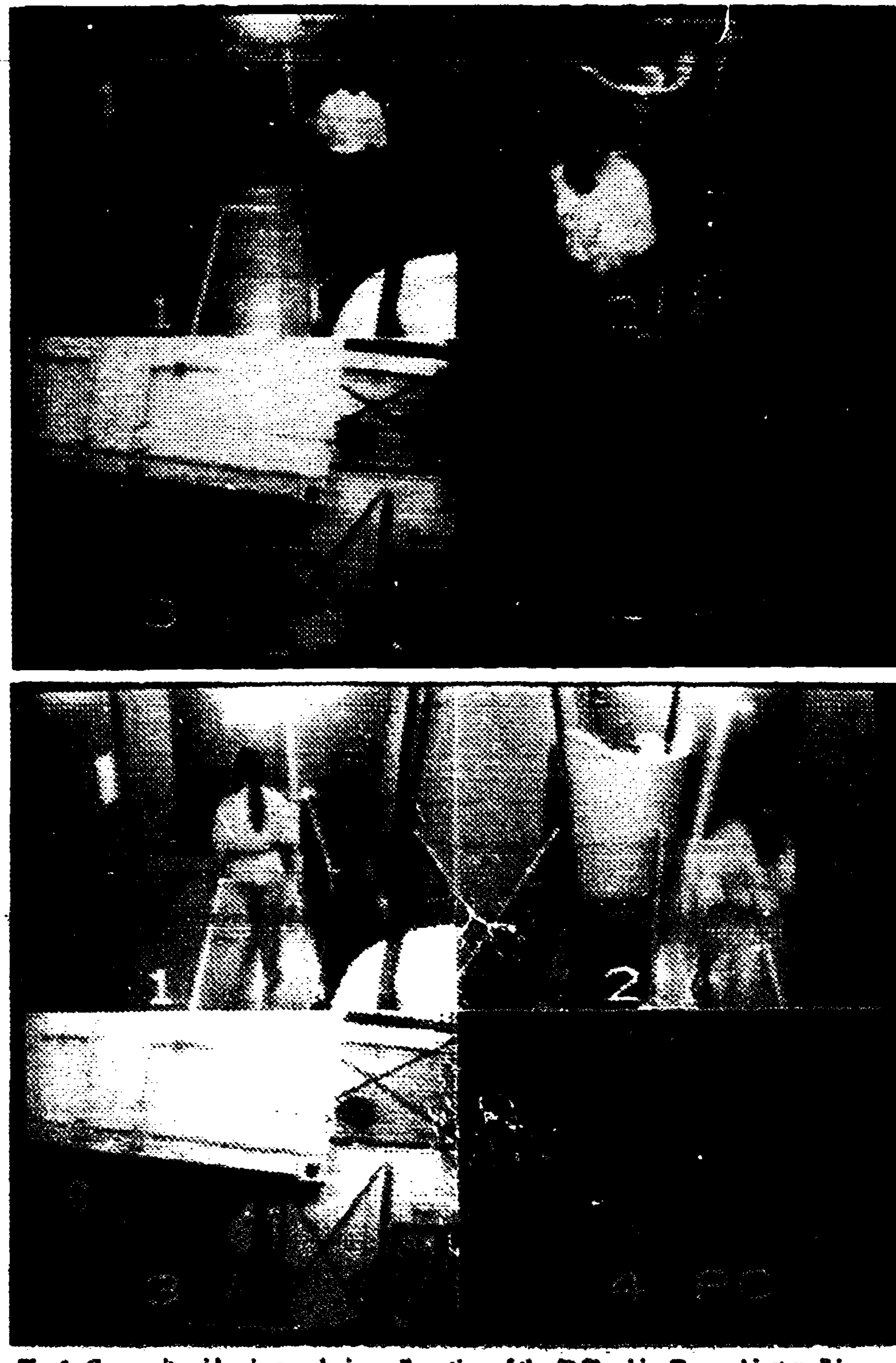

Fig. 1 Composite video image during roll motion of the SMS cabin. Top: subject walking on the treadmill. Bottom: subject walking on the floor. Upper left: view on subject by camera at front wall. Upper right: view on subject by camera at rear wall. Lower left: outside view of the SMS cabin (only the lower section of the cabin is visible together with the upper section of the hydraulic system; note roll motion of the cabin). Lower right: display of the computer generated SMS steering parameters.

3.1 Ventilatory parameters

3.1.1 *Oxygen consumption*

Oxygen consumption ($\dot{V}O_2$) during roll and pitch was significantly higher than during the stationary and heave conditions (Fig. 2). The differences between the roll and pitch conditions themselves were not significant, nor were those between the heave and stationary conditions.
The $\dot{V}O_2$ for treadmill walking was lower than for free walking and there was a significant interaction between walking and gender (Fig. 3).
This pattern of results does not change if the $\dot{V}O_2$ is compensated for body weight or body length (i.e. if measurements are expressed in terms of oxygen consumption per kg body weight and length).

3.1.2 *Carbon dioxide production*

Mean carbon dioxide production ($\dot{V}CO_2$) is also higher during roll and pitch conditions compared to stationary and heave conditions, and again there are no significant differences between roll and pitch and between stationary and heave (Fig. 4).
Treadmill walking produced significant lower $\dot{V}CO_2$ levels (807ml on average) than free walking (998ml on average).

3.1.3 *Minute ventilation*

This parameter showed again the same effect: during pitch and roll conditions $\dot{V}_E$ was significantly higher than during heave and the stationary conditions, and again there was no significant difference between pitch and roll and between heave and stationary conditions (Fig. 5).
Minute ventilation during free walking was more voluminous (33 l/min) than during treadmill walking (27 l/min).

3.1.4 *Metabolism*

For metabolism the picture was the same again: no difference was observed between roll and pitch, and both differed significantly from the heave and stationary conditions, which did not differ from each other (Fig. 6).
During treadmill walking the metabolism index was lower than during free walking. On this parameter there again appeared to be a significant interaction between gender and mode of walking (Fig. 7). This interaction also remained significant when the data were compensated for body weight and length, just as observed with the $\dot{V}O_2$ parameter (which is not surprising, because mathematically this $\dot{V}O_2$ parameter is an important part of the metabolism index).

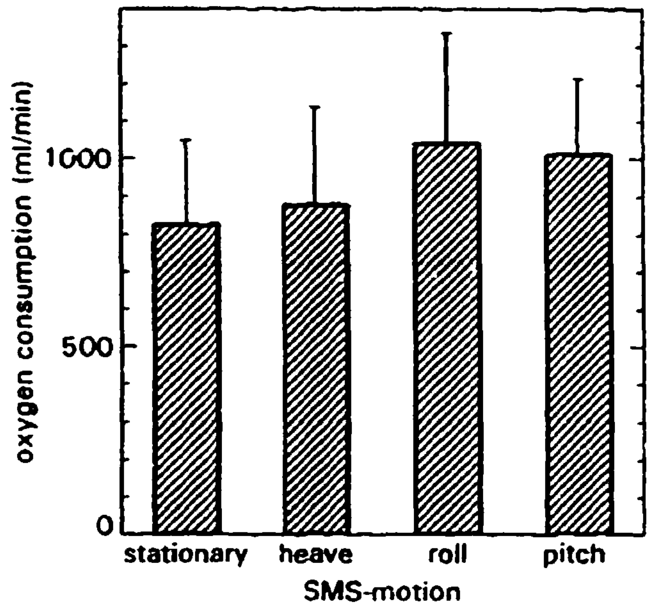

Fig. 2 Mean oxygen consumption (and standard deviations) during the stationary, heave, roll and pitch conditions of SMS motion.

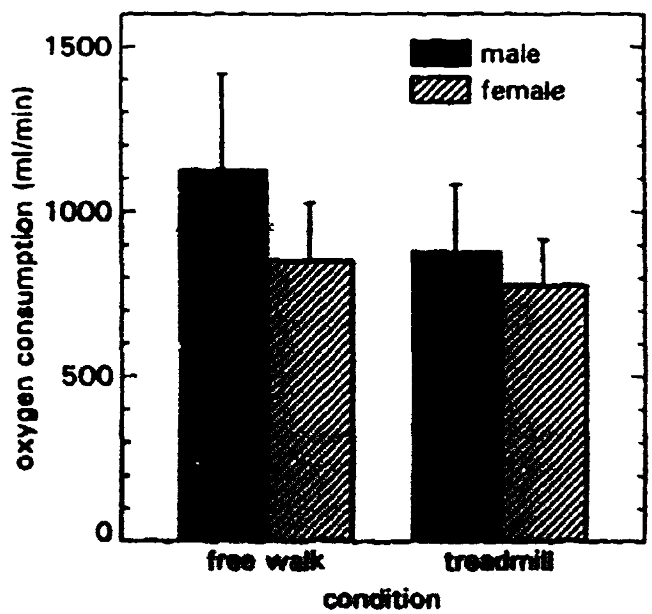

Fig. 3 Mean oxygen consumption (and standard deviations) for male and female subjects during treadmill and free walking inside the SMS.

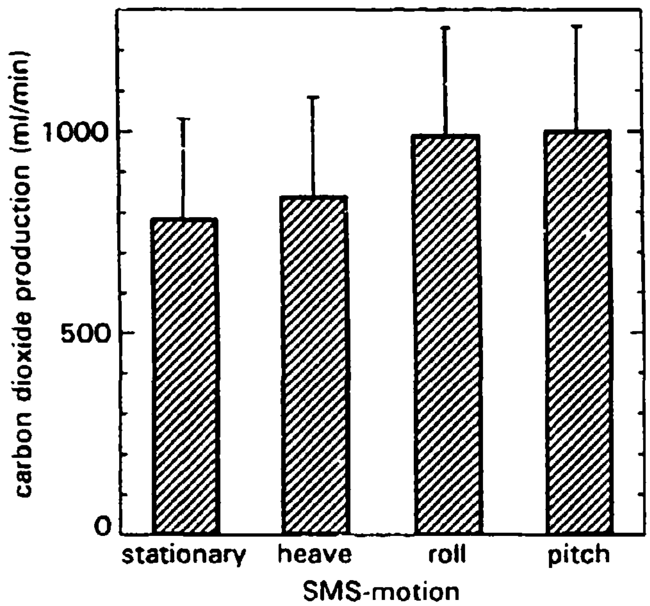

Fig. 4 Mean carbon dioxide production (and standard deviations) during the stationary, heave, roll and pitch conditions of SMS motion.

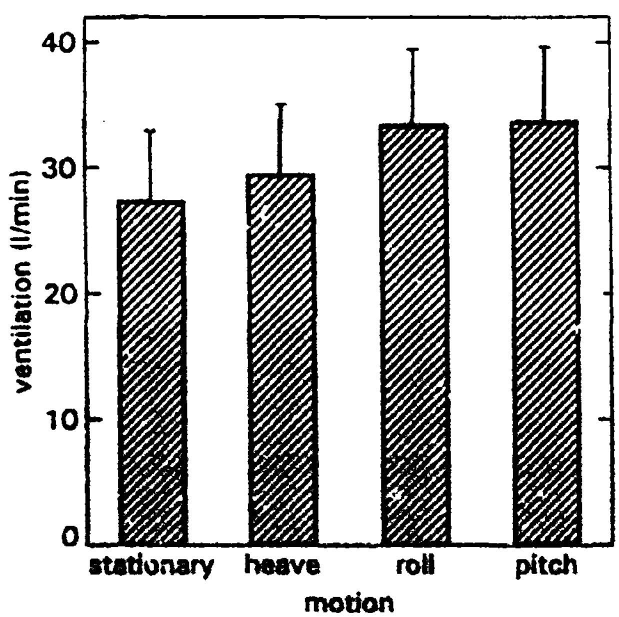

Fig. 5 Mean minute ventilation (and standard deviations) during the stationary, heave, roll and pitch conditions of SMS motion.

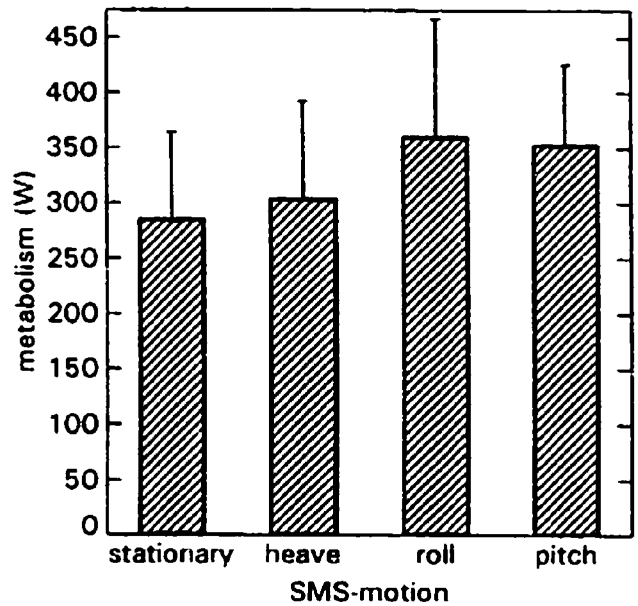

Fig. 6 Mean metabolism (and standard deviations) during the stationary, heave, roll and pitch conditions of SMS motion.

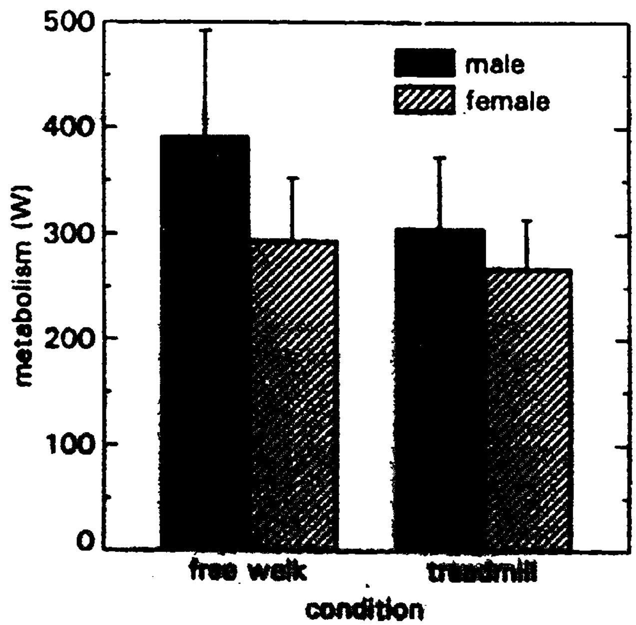

Fig. 7 Mean metabolism (and standard deviations) for male and female subjects, during treadmill and free walking inside the SMS.

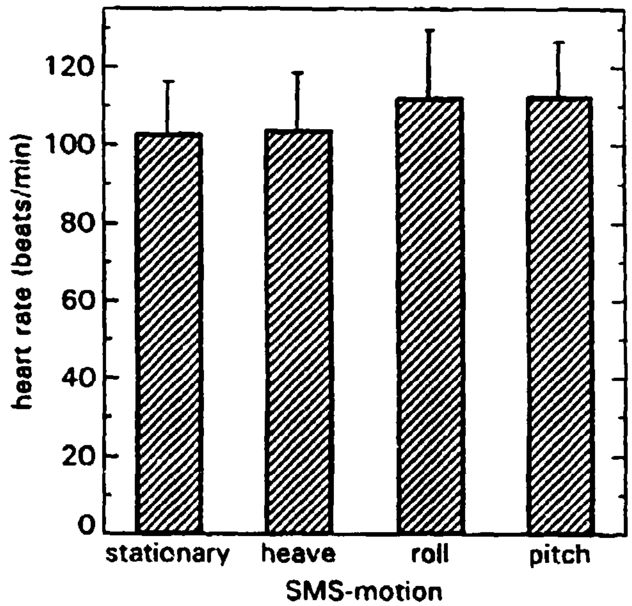

Fig. 8 Mean heart rate (and standard deviations) during the stationary, heave, roll and pitch conditions of SMS motion.

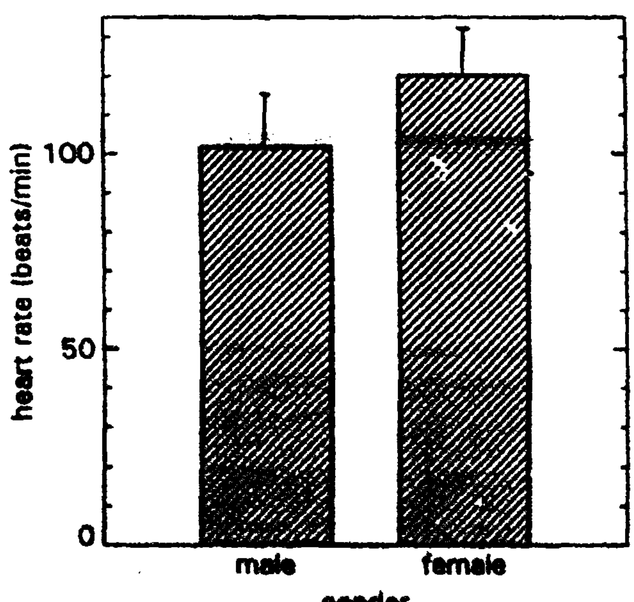

Fig. 9 Mean heart rate (and standard deviations) for male and female subjects.

3.2 Heart rate

The mean heart rate showed the same trends as the ventilatory parameters: heart rate did not differ between the heave and stationary conditions and also not between roll and pitch conditions, but the former two showed a significantly lower heart rate than the latter two (Fig. 8).
There were significant over all gender differences: male subjects had significantly lower heart rates than female subjects (Fig. 9).

3.3 General performance

Since it was not the purpose of the present to study the occurrence of balance problems during the measurements periods, we did not score them. However, a future analysis of the video records remains possible (although it might prove quite time consuming). At this stage we can only confirm that subjects did indeed sometimes show evidence of balance problems (e.g. they often used the handrails of the treadmill for support).

4 DISCUSSION AND CONCLUSIONS

In this study significant effects of different movements of the SMS were found on the energy expenditure of subjects walking inside the SMS. More in particular, roll and pitch movements of the SMS caused higher $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and heart rate values than heave motions of the SMS and when the SMS remained stationary. The absence of an effect of heave motion is not surprising. The effects on energy expenditure observed in the roll and pitch conditions of the present study, are most likely caused by an increased energy consumption required by the extra muscular effort needed to maintain balance while walking in a moving environment. This extra effort is expected mainly to happen in the pitch and roll conditions, because only here is it necessary to correct the direction of the vertical body axis away from the subjective vertical (which is largely dependent on visual information and therefore more or less perpendicular to the cabin floor) and align the body axis to the true vertical (using vestibular and kinaesthetic information). In the heave and stationary conditions the direction of the subjective vertical and of the true vertical always remain identical. Hence, it is unlikely that subjects might have had problems maintaining their balance in those conditions, especially since the vertical accelerations were also quite low.

The most likely explanation for the difference between free walking and treadmill walking on the ventilation indexes, is that two factors have caused it. First, in the free walking conditions all subjects had repetitively to turn around and change their walking direction 180 degrees (relative to the length axis of the cabin. That causes extra muscular effort. Second, in the free walking condition

there is, on every turn, a need to first decelerate and then accelerate again to keep up with the required average speed of walking as forced upon the subject by the regularly sounding beeps. Such a variable velocity profile in the free walking conditions is likely to require extra muscular activity of the leg muscles. It is not possible to register the actual percentage of time spent on straight walking vs turning, because the point where the one changes into the other cannot be determined in any standardised manner, not in the least because there appeared to be many individual walking stiles. In this respect, behaviour on the treadmill was much more uniform. Therefore, it is recommended to use only treadmill walking as a standard task in future research.

The gender effects, illustrated in Figs 3 and 7 are difficult to interpret. They cannot be explained as the result of biomechanical differences between men and women, because they remain significant when we compensate for body weight and length. As long as the effect is not replicated we would like to refrain from speculative explanatory hypotheses. Hence this is an issue that might be included in further studies.
The higher heart rate observed with female subjects as compared to male subjects (Fig. 9) reflects a constitutional difference between men and women, which is normally observed in this kind of studies (see e.g. Johnson & Lubin, 1972; Seele, Guzman & Becklake, 1974; Holewijn, Heus & Wammes, 1992).

From the present study we may conclude that walking on a platform that moves in pitch or roll directions causes more energy consumption than when the platform remains stationary, or when it makes only (small) heave movements. However, it is not possible to draw conclusions about the absolute energy expenditure of our subjects. In other words, we cannot answer questions like: how long would it take for a walking subject before he or she becomes fatigued on a moving platform as compared to a stationary platform. To obtain an absolute indication of energy expenditure one needs to compare the present energy expenditure values to the energy expenditure values obtained when the subject works at his or her maximum capacity (e.g. during maximum performance on the treadmill). In the present study we have not included a preliminary condition in which this maximum energy expenditure was measured. This issue will be taken up in future research.

Other issues for future research are the effects of combined heave, roll and/or pitch motions, and energy consumption as a function of the amplitude of heave, roll and/or pitch motions of the SMS. A final goal of such a research program would preferably be the formulation of a quantitative relation between ship motion parameters and energy expenditure.

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Dr. A.H. Wertheim

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The effect of platform motion on human energy expenditure during walking. An exploratory experiment

11. AUTHOR(S)

A.H. Wertheim, R. Heus, T.G.M. Vrijkotte and J.T. Marcus

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Institute for Human Factors IZF
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

TNO Defence Research
Schoemakerstraat 97
2628 VK Delft

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

An experiment was performed in which various physiological measures of energy expenditure were taken with subjects walking for periods of 10 minutes (either freely or on a treadmill) on a moving platform (Ship Motion Simulator). Platform motion was either in a heave, pitch or roll mode, or it was stationary. The results show that during pitch and roll movements of the platform energy expenditure is larger than during heave motions and when the platform remained stationary. Pitch and roll did not differ from each other, and neither did heave and stationary conditions. The results are interpreted as indicating that the muscular effort needed for the maintenance of balance when walking on a pitching or rolling platform requires a significant increase in energy expenditure.

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